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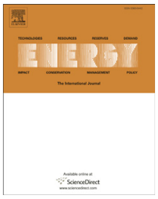

3E (energy, environmental, and economy) evaluation and assessment to an innovative dual-gas polygeneration system

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ABSTRACT

To resolve problems surrounding simultaneous CO_2 conversion and COG (coke oven gas) utilization, a novel system combining a dual-gas of CGG (coal gasified gas) and COG with the technology of CO_2 recycling into a single gasifier and reforming unit is proposed. 3E performance (energy, environmental, and economic) analysis showed that this novel system renders unnecessary the traditional water–gas shift process, and realizes the conversion and utilization of CH_4 and CO_2 that would otherwise be directly discharged into the air. Under a weak carbon mitigation policy, the economics of co-producing low-carbon fuels and electricity from a dual-gas of CGG and COG are promising. The "dual-gas" technology is a potentially viable option for clean coal and its efficient use in the co-production of low-carbon fuels and electricity in areas possessing COG, natural gas or other unconventional natural gas resources.

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1. Introduction

In the search to find ways to cleanly and efficiently use coal, many kinds of technologies have been investigated. IGCC (integrated gasification combined cycle) with CCS (carbon capture and sequestration) is a common power generation system used to efficiently reduce CO_2 emissions, and different CO_2 emission reducing technologies such as physical absorption, membrane reactors, chemical looping, oxy-fuel combustion and other related technologies have been studied [1–3]. The above technologies can achieve about a CO_2 recovery rate of approximately 90%, but will incur a thermal energy loss between 7 and 13% and also a 20 and 30% increase in investment cost [4,5]. The estimated costs for CO_2 transportation (US\$ 1–3/(t·100 km)) and sequestration (4–8 US\$ t^{-1}-CO_2) are lower than that of CO_2 capture, which is estimated at 35–55 US\$ t^{-1}-CO_2 captured. The high cost of CO_2 capture stems from the considerable amount of energy required in the separation process and extra equipment investment [6].

Polygeneration system, integrating the IGCC with chemicals production, could be an option for solving the balance between energy production and economic benefit. For instance, the production costs of methanol in a methanol/electricity polygeneration plant could be 40% lower than that in a stand-alone methanol plant, and resulted in about 3.9% energy saving [7,8]. In order to investigate the reliability and tap potential of polygeneration system, Liu [7] proposed a multi-objective optimization approach to improve the total efficiency of the polygeneration system, Gao [9] and Li [10] researched polygeneration plant with methanol/nature gas/electricity products by use of exergy analysis, and revealed the essence for energy efficiency upgrade of polygeneration plant. Economic analysis and assessment of a coal based polygeneration system with CO_2 capture indicated that a co-production plant with high CO_2 recovery can simultaneously achieve higher energy utilization and economic benefits. The thermal efficiency of polygeneration plant with 90% CO_2 capture was about 7–16% higher than that of IGCC or coal-pulverized supercritical plant with 90% CO_2 capture, and the unit investment of the polygeneration system could be decreased to 600–900 US\$ kW^{-1} through plant efficiency upgrade [11]. Polygeneration system with CCS is an energy efficient and carbon mitigation initiative technology. However, most of the aforementioned CCS technologies based on the polygeneration system do not take into consideration CO_2 treatment, transport and storage after the CO_2 is separated out. As Hetland [12] pointed out: "just

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Nomenclature

Abbreviations

CAPEX	the unit capital expenditures, US$
$CO_{2\ avoided}$	cost of CO_2 avoided, US$ t^{-1}
$CO_{2,R}$	CO_2 emission reduction of the systems, t y^{-1}
$CO_{2,Tax}$	CO_2 tax price, US$ t^{-1}
COE	cost of electricity, US$ kWh^{-1}
COE_{CCT}	COE of systems with CO_2 capture or use considering benefits from CO_2 tax, US$ kWh^{-1}
IRR	internal rate of return, %
OPEX	operating expenditures, US$ y^{-1}
P	power output of the plant, MW

Acronyms

3E	energy, environmental and economy
ASPEN	advanced system for process engineering
ASU	air separation unit
ATR	autothermal reforming
BGL	British gas Lurgi
Capture plant	IGCC–CCS, IGCC–CRS, PL–CCS
CCS	carbon dioxide capture and sequestration
CF	the plant capacity factor
CGG	coal gasified gas
COG	coke oven gas
CT	chemicals transportation
DGP	dual-gas polygeneration
GHG	greenhouse gas
HHV	high heat value
IGCC	integrated gasification combined cycle
LHV	lower heat value
M	million
MeOH	methanol
Mt	million tons
NG	natural gas
PM	particulate matter
PT	power transportation
RAU	reforming auxiliary unit
Reference plant	IGCC
SMR	steam methane reforming
TUT	Taiyuan University of Technology
UNG	unconventional natural gas
US$	US dollar
WGS	water gas shift
WGSR	water gas shift reactor

capturing the CO_2 without storage makes no sense". In actuality, CO_2 transportation requires high quality pipeline materials and the cost of transportation rises with the prolonged distance, along with some geopolitical risks [13]. Jillson [14] and Oki [15] designed the oxy-fuel IGCC with CO_2 recycle to gasifier for CO_2 use and capture, the system thermal efficiency was more than 40% even after capturing CO_2, as high as that of a state of the art IGCC plant. Yi [16] proposed polygeneration system with CO_2 recycle and use, and the new system realized 11.5% increase of chemical exergy, 1.3% increase of internal rate of return and 33.8% reduction of CO_2 emission. CO_2 recycling would be a suitable way to convert CO_2 into CO for chemical synthesis and liquid fuel.

As the main by-product of the coal coking process, COG (coke oven gas, containing 6 vol% CO, 59 vol% H_2, 26 vol% CH_4, 3 vol% CO_2, and 6 vol% N_2) is a presently underutilized hydrogen-rich product [17]. Approximately 400 million tons of coke, more than half or the world's annual coke production, is generated by China, with a resulting by-product of about 1.6×10^{11} m^3 of COG. However, only half of this COG is burnt to supply heat through recycling back into the coke oven, an inefficient process which only consumes 10% of the available COG [18]. The implications are that 95% of COG produced is either directly released into the atmosphere or discharged after combustion, not only wasting a potential energy resource but also contributing significantly to air pollution. Since COG is rich in hydrogen and methane, and CGG (coal gasified gas) is rich in carbon, the mixture of COG and CGG could adjust the mole ratio of C/H in the syngas by either ATR (autothermal reforming) or SMR (steam methane reforming) [19] instead of the conventional WGS (water–gas shift) process. As a result, a D-PL system (dual-gas polygeneration), which combines coal and COG to simultaneously produce ultraclean synthetic fuels and electricity, has attracted much interest since first being proposed [20]. The D-PL would efficiently utilize CH_4 in COG and CO_2 in CGG and thereby reduce GHG (greenhouse gas) emissions. Particularly in comparison with stand-alone production, the benefits of the D-PL system are significant in the areas of capital investment, cost of unit product and pollution reduction, as well as energy efficiency [21].

This paper aims to address the problems surrounding the conversion and use of CO_2 and simultaneous COG utilization. Based on previous research [21,22], a novel system – D-PL-CR (dual-gas polygeneration system with CO_2 recycling) – was proposed. In order to investigate the overall performance and potential advantages of the novel system and assess the feasibility and reliability of its future application, the novel system as a case study was researched in the coal chemical industry park of Xinzhou city, Shanxi. 3E (energy, environmental, and economy) analyses of D-PL-CR are presented.

2. System design

The D-PL system was implemented on a pilot scale in Xinzhou, Shanxi, and the novel system (D-PL-CR) Fig. 1 proposed on the basis of the D-PL [22]. Coal is gasified with steam and oxygen, which is from ASU (air separation unit). High temperature flue gas is fed into a waste heat boiler in order to vaporize the supplied water and produce the saturated steam necessary for the power generation system. After cooling and removal of particulates, the cooled gas enters into thick-desulfurization tower and fine-desulfurization tower successively, and the concentration of (H_2S + COS) in the clean gas are reduced to below 1 ppm, which can effectively avoid the adverse effects of sulfur on the reforming catalysts and synthesis catalysts in the subsequent process. The resultant clean gas is mixed with purified COG and recycled CO_2 before entering the CH_4/CO_2 reforming unit. Energy for the reaction is provided by the direct combustion of partially unreacted gas in the RAU (reforming auxiliary unit). The resulting clean syngas is compressed to 6.5 MPa, and then is sent into methanol (MeOH) in the synthesis reactor. After processing in the synthesis reactor, CO_2, MeOH and water are separated out from the unreacted gas. Two distillation towers were used in the separation process: the first to separate out CO_2, the second to separate out MeOH and water. A portion of the separated CO_2 (95 wt%) is recycled back into the gasifier, and the remainder used in the reforming unit. Part of the unreacted syngas underwent compression and was then recycled for use in the synthesis reactor,

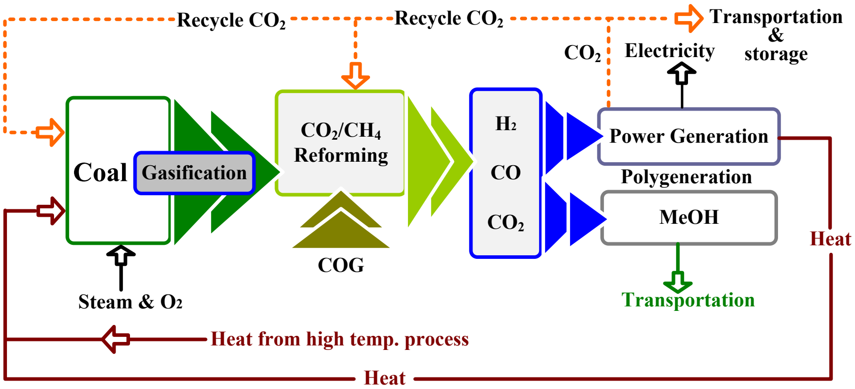

Fig. 1. Schematic of a dual-gas polygeneration system for power and methanol production with CO_2 recycles.

while the remaining unreacted syngas was employed to supply energy to the RAU and the power generation subsystem. The power generation system supplies the power and the steam required in the previously discussed processes. The main difference between the design of D-PL-CR and D-PL is that the former provides the two schemes for CO_2 recycling while the later provides for only one.

The most desirable features of D-PL-CR are the inclusion of two feedstock and CO_2 recycling points, unlike most proposed IGCC–CCS plants. The use of COG, a cheap and hydrogen-rich resource in an integrated coal process can realize reasonable and effective use of resources whilst reducing CO_2/CH_4 reforming technology and CO_2 recycling in gasifier and reforming unit design could realize the conversion and use of excess CO_2 and postpone GHG emissions without necessitating the use of CCS. CO_2 conversion into CO increases syngas, which in turn increases chemicals output, and it can be seen as an effective way to improve carbon element utilization and reduce coal use. Although CO_2 will eventually be emitted because of the combustion of liquid fuels or the use of chemicals, such as methanol, dimethyl ether, gasoline etc., the D-PL-CR system can reduce the overall in-unit CO_2 emissions and delay CO_2 emissions over the entire life cycle. Thus, the immediate stress on the environment is decreased and greenhouse effects avoided as the environment is less likely to be taxed beyond its capacity to absorb and decompose CO_2 at any given time. Overall, the whole process is simplified and conventional water–gas shift reaction, CO_2 separation and capture and other issues related to CO_2 handling can be avoided. In order to reveal the energy saving, economic benefits and emission reduction potential of the D-PL-CR system, the PL–CCS [5], IGCC, IGCC–CCS (IGCC with CCS) and IGCC–CRS (IGCC with CO_2 recycling and storage) [16], which have the potential to improve process efficiency, reduce capital and operating expenses and increase system availability and can be probable achievement of the large-scale commercialization for coal use in the near future [21], are compared with the new system.

2.1. Modeling, assumption and validation

All the systems were simulated by Aspen Plus 11.1. Operation conditions and technological specifications of key units were listed in Table 1. The verification step is essential to the validity of the simulation results, especially when modeling complex processes. The choice of model for each process, process assumption, property methods and detailed modeling can be found in the previous work [16,21]. The previous results showed that the major simulation results of all the investigated systems in this work were in good agreement with the experimental results and literature data from IGCC simulation by Zhang [23], syngas clean process simulation by Sun [24] and polygeneration system with CCS by Zhou [25]. What's more, most of the data on economic analysis comes from IGCC demonstration (Huaneng GreenGen project) and D-PL pilot project. Therefore, the 3E results of the systems have a certain reliability and reference values. Aspen Plus simulation diagrams of each system are shown in the appendix A – Supplementary Data.

2.2. System boundaries for 3E assessment

The boundaries and evaluation methods utilized for the investigated systems are presented in Fig. 2. The scope in terms of 3E

Table 1
Technologies choice for systems.

Item	Units	IGCC, IGCC–CCS, IGCC–CRS, PL–CCS		D-PL, D-PL-CR	
Gasifier	Temperature (°C)	1400	Texaco gasifier	1050	Ash-agglomerating fluidized bed gasifier
	Pressure (MPa)	7		0.51	
Desulfurization	Temperature (°C)	40	MEA/clause	500	$Fe_2O_3/SiO_2/Al_2O_3$ (thick desulfurization)/
	Pressure (MPa)	2		0.1–0.8	$ZnFe_2O_4/SiO_2/Al_2O_3$ (fine desulfurization)
CH_4/CO_2 reforming reactor	Temperature (°C)		/	900	$Ni/La/Al_2O_3$
	Pressure (MPa)			0.1	
	SV ($L\ h^{-1}\ kgcat^{-1}$)			3000	
Water gas shift reactor	Temperature (°C)	420	$CoO/MoO/\gamma\text{-}Al_2O_3$		
	Pressure (MPa)	4		/	
	SV ($L\ h^{-1}\ kgcat^{-1}$)	3000			
Methanol synthesis reactor	Temperature (°C)	260	$CuO/ZnO/Al_2O_3$	260	$CuO/ZnO/Al_2O_3$
	Pressure (MPa)	6		6	
	SV ($L\ h^{-1}\ kgcat^{-1}$)	5000		5000	
Gas turbine	Compression ratio	15.7	GE-7FA	15.7	GE-7FA
	Firing temperature (°C)	1288		1288	
	Exhaust temperature (°C)	604		604	

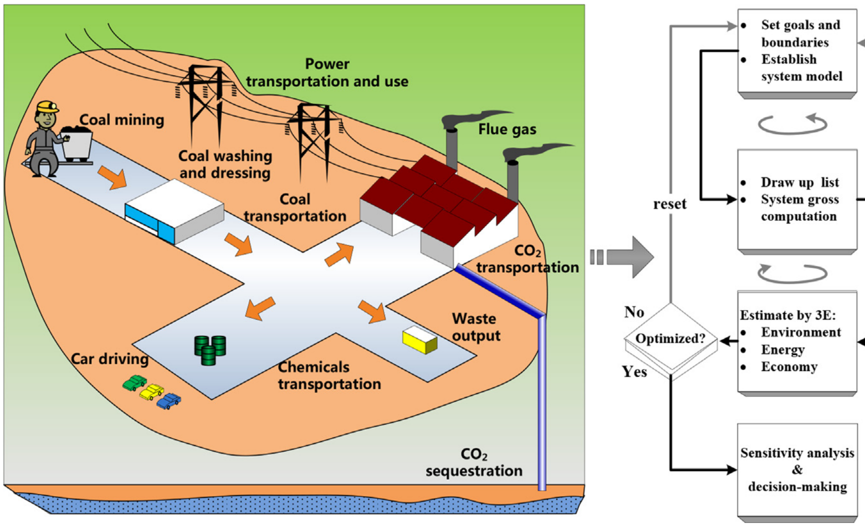

Fig. 2. System boundary and fundament principle of life cycle assessment.

performance in life cycle covered the phases of coal processing and utilization, CO_2 gas compression, transport and storage, and upstream processes such as coal exploitation and transportation, as well as product transportation and use [26,27]. By quantifying the input/output relationship and preparing an inventory of input/output data for all component processes involved in the life cycle of the system(s), the magnitude and significance of the potential 3E impact of a product system were evaluated for various processes. Finally, limitations were detected using sensitivity analysis. The energy necessary for the operation of the CCS is assumed to reduce the net power output. CO_2 from the plant is compressed to the super-critical state at a pressure of 15 MPa, and the data and calculation of energy loss in CO_2 transportation and storage process were obtained from literature [5]. Since it is assumed that depleted gas fields will have pre-existing storage facilities, there is no need to calculate cost for the additional storage infrastructure. As the investigated energy systems represent a future technology, data for emissions to water and soil – more difficult to predict than atmospheric emissions – were not available and therefore could not be evaluated [28].

The coal used in the systems is from Shanxi province, China. Its ultimate analysis, proximate analysis and LHV (lower heat value) are shown in Table 2. In an economic assessment process, key economic parameters which could initially be taken into account are summarized in Table 3. (All cost/prices are given in an average of 2010 US$ (US dollar) values). As a basis for comparison, each case is designed with a net output of 300 MW.

3. Results and discussions

3.1. Analysis on CO_2 recirculation

In this paper, two CO_2 recirculation pathways are proposed for the novel system. The first method, particularly suitable for the D-PL system, recycles CO_2 to the reforming unit, where the following reaction occurs: $CO_2 + CH_4 = 2CO + 2H_2$ $\triangle H = +247$ kJ mol^{-1}. The main feature of this scheme is that, instead of being a waste gas, CO_2 takes part in the reaction as a feed gas and is converted into CO, which not only reduces CO_2 emission but also increases carbon resource utilization. The reaction conditions optimization of CH_4/CO_2 reforming unit, and the effect of CH_4/CO_2 reforming reaction on CH_4/CO_2 conversion of the whole system have been deeply researched. The results showed that the carbon element conversion efficiency improved dramatically and CO_2 emission could reduce by 30%–50% if having CH_4/CO_2 reforming [19,21]. The second method of CO_2 recirculation is to re-inject the separated CO_2 into the gasifier as a gasification agent, which then react with coal at temperatures above 1073 K. According to the industry demonstration, it is possible to use a portion of CO_2 instead of H_2O as the gasification agent [29]. On the one hand, water consumption can be reduced and carbon element utilization improved; on the other hand, gasifier temperature can be controlled by a suitable ratio of CO_2/H_2O (kg kg^{-1}). The Texaco gasifier was taken as a case study to illustrate the effect of CO_2 recycling on a gasifier in the literature [16]. Substituting CO_2 for a portion of the water recycled to the gasifier as the gasification agent will decrease H_2, while increase CO and CO_2, as well as coal water slurry concentration. However, the gasifier temperature can be kept relatively stable. In order to obtain the slurry concentration of 58 wt%–70 wt% that is suitable for the Texaco gasifier, and an appropriate gasified gas composition for

Table 2
The properties and heat value of coal sample.

Proximate analysis, wt%				Ultimate analysis/daf, wt%					LHV/MJ kg^{-1}
M_{ad}	V_{ad}	FC	A_{ad}	C	H	O	N	S	
2.81	11.31	71.1	14.78	94.32	2.83	1.21	1.31	0.34	27.1

Table 3
Generic economic parameters of the six systems.

Items	Value
Raw coal price (US$ t^{-1})	60
Coke oven-gas price (US$ m^{-3})	0.05
Discount rate (%) [16]	12
Design (y) [16]	2
Process water (US$ t^{-1})	0.13
Cooling water (US$ t^{-1})	0.03
Depreciation life (y) [16]	15
Run time (d y^{-1}) [16]	300
Construction life (y) [16]	3
Operation (y) [16]	30
Tax rate (%) [16]	20
Production capacity [16]	95% of designed capacity
Methanol price (US$ t^{-1})	400
Feed-in tariff (US$ kWh^{-1})	0.06

Table 4
Energy distribution and CO_2 emissions in each stage of the life cycle.

	IGCC	IGCC–CCS	IGCC–CRS	PL–CCS	D-PL	D-PL-CR
	Energy distribution (%)/CO_2 emission (kg kg^{-1}-coal)					
Coal mining and transportation	5.35/0.098	5.35/0.098	5.35/0.098	5.35/0.098	5.35/0.094	5.35/0.094
Coal conversion and utilization	53.35/3.071	58.49/0.275	53.78/0.092	47.13/0.658	41.25/1.223	39.07/1.216
Power	38.38	29.95	33.94	12.71	19.93	20.72
Chemicals				27.69/0.002	30.93/0.002	32.34/0.002
Power transportation	2.92	2.73	2.71	1.03	1.54	1.52
Chemicals transportation				1/0.283	1/0.21	1/0.18
CCS		3.48	4.22	5.09		
Total	100/3.169	100/0.373	100/0.19	100/1.041	100/1.53	100/1492

downstream production and the overall performance of the system, a suitable recycling ratio of CO_2 is the key to this scheme. Here, the optimal ratio of CO_2 mass flow to coal mass flow – CO_2/coal (kg kg^{-1}) is 0.4 for the Texaco gasifier and 0.11 for the ash-agglomerating fluidized bed gasifier. The method of choosing the appropriate CO_2 recycling ratio and the effects of CO_2 recycling on system performance are presented in detail in a previously published work [16].

3.2. *Thermal performance*

Fig. 3 shows the gross electricity production from the six systems under comparison. The PL–CCS system displays the highest electricity production at 594 MW, but the PL–CCS also shows the greatest power consumption of 293 MW, consumed by the gasification (including ASU) and gas compression processes. Gas compression includes gas synthesis, a gas compression cycle and acid gas removal, accounting for 25% of total power output. Approximately 6% of the gross electricity produced is consumed in the CO_2 capture and sequestration processes. Other energy consumptions include the pumping and cooling of water. The IGCC–CRS system is the second largest power consumer as the pure oxygen combustion technology in the ASU with a high power cost, about three times that of the IGCC system. In comparison, at equal net electricity outputs (300 MW), it is obvious that both D-PL and D-PL-CR exhibit the lowest power consumptions in the gasification process due to the use of COG instead of partial coal gasification, reducing the amount of power consumed by the ASU to supply oxygen.

Table 4 shows energy distributions and CO_2 emissions of the systems in different phases over the energy life cycle. The phase of coal processing and utilization is obviously the point at which the majority of the energy loss occurs in all six systems. Energy loss for the D-PL-CR system is about 8% lower than that of PL–CCS, and 15%–18% lower than IGCC, IGCC–CCS and IGCC–CRS at this stage. That is mainly because D-PL-CR integrates the chemical process and the power generation system, initially using high grade syngas for chemicals synthesis, and then low grade unreacted gas in the power generation system for electricity production. As a result, the co-production of chemicals enhances the total energy output of the entire polygeneration system. Another significant factor is that CO_2 recycling improves chemical energy utilization and reduces energy consumption in the gasification process, potentially saving 10% of the energy input.

3.3. *Environmental performance*

From Table 4, it can be observed that CO_2 emissions primarily result from the coal processing and utilization stages, most of which can be substantially reduced by using CCS technology. CO_2 emissions of the IGCC–CCS/CRS systems are less than 0.40 kg kg^{-1}-coal, while those of PL–CCS reach nearly 1.04 kg kg^{-1}-coal. D-PL-CR does not involve the capturing and sequestration of CO_2, but the life cycle CO_2 emissions of D-PL-CR also have a lower value of 1.49 kg kg^{-1}-coal, far less than that of IGCC (3.17 kg kg^{-1}-coal). More to the point, the D-PL-CR system does not require CCS facilities and avoids the risks of geological CO_2 storage. Methanol transportation and utilization (annual consumption of 40% of total chemicals as liquid fuel) is another substantial source of CO_2 emissions. The cost of CO_2 avoided ($CO_{2\ \mathrm{avoided}}$) is widely used to measure the cost of reducing CO_2 emission by a mass unit (t kWh^{-1}), and can be calculated using the formula (7) in Ref. [25].

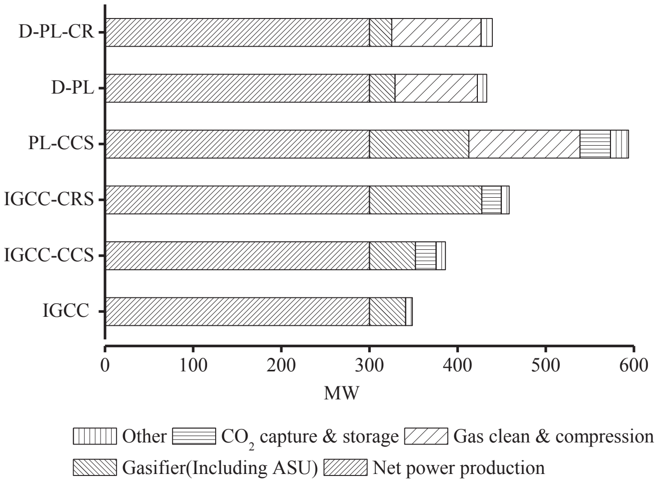

Fig. 3. Electricity production output and consumption in different processes.

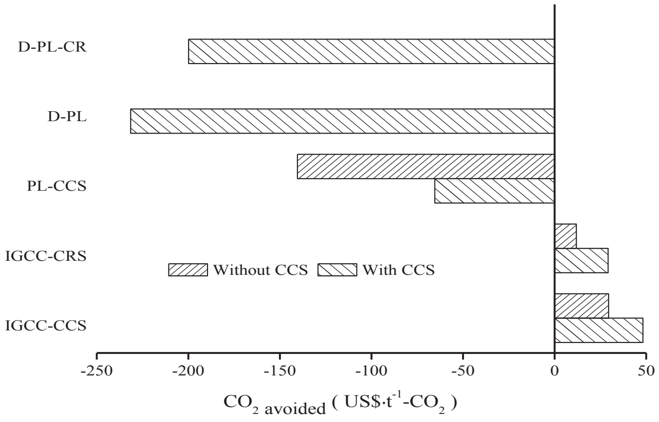

Fig. 4. Cost of CO_2 avoided with/without considering CCS cost on the basis of IGCC reference system.

As shown in Fig. 4, it is apparent that CO_2 avoided of polygeneration systems (PL–CCS, D-PL and D-PL-CR) is a negative number, and much lower than that of IGCC–CCS/CRS. That's because the co-production chemicals reduce the COE (cost of electricity) as compared with the reference plant (IGCC). In addition, when the cost of CCS is added to the systems, CO_2 avoided increases sharply compared with CCS cost is not taken into consideration (e.g. IGCC–CCS/CRS increases by about 20 US\$ t^{-1}, and PL–CCS increases by 80 US\$ t^{-1}). As a result, reducing the cost of CCS significantly enhances the economic performance of CO_2 reduction. D-PL-CR utilizes CO_2 recycling instead of CCS, reducing the requirement of investment in CCS facilities and operation costs, implying that new D-PL-CR technology reduces CO_2 emissions at a low cost while maintaining high energy efficiency, rendering it a competitive alternative to current technology in today's market. Furthermore, D-PL-CR shows that the best performance in conventional pollutants emissions due to lower coal consumption and pollution emission reduction by COG replacing a part of coal. Fig. 5 shows SO_2, NO_x and PM (particulate matter) emissions in grams per kWh. It is clear that SO_2 and NO_x emissions in IGCC/polygeneration system are also far lower than those of supercritical power plants employing desulphurization, denitration and dedust (0.6–0.7 g kWh^{-1}) with PM emissions below 0.01 g kWh^{-1}.

3.4. Economic performance

3.4.1. The CAPEX (total capital expenditures)

The scales of the systems can be obtained from simulation processes, and the total capital investment of each system can be calculated by Profitability Analysis-1.0.xls [30] and the production scale index method [31]. The reference scale parameters and capital costs data of IGCC and D-PL are based on the demonstrated Huaneng GreenGen project and D-PL pilot project, and the other systems' basic capital cost data of facilities can be obtained from Refs. [8,32–34]. As seen in Table 5, the total CAPEX of IGCC is US\$ 452.02 million and its unit CAPEX is 1506.74 US\$ kW^{-1}. The CAPEX of IGCC–CCS and IGCC–CRS are greater than that of IGCC by 36.90% and 23.78% respectively. For the integrated chemical process and power generation system, the initial investment required for PL-CCS is about 150% of that of IGCC. However, initial investment for D-PL-CR, while still higher than that of IGCC, is 20% lower than that of PL–CCS.

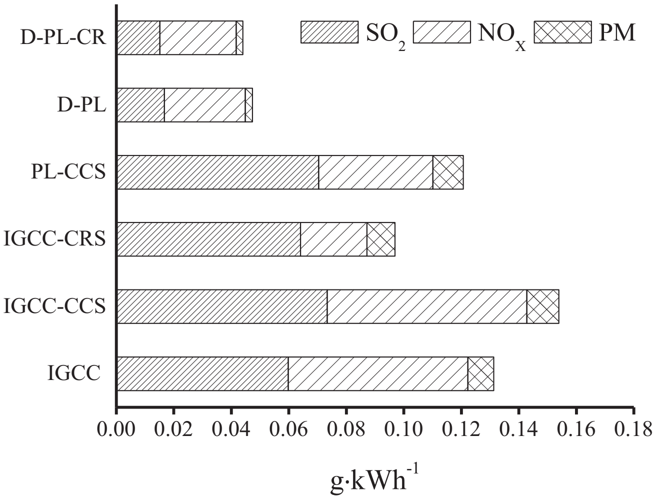

Fig. 5. The environmental impacts of conventional pollutants from different systems.

3.4.2. OPEX (operating expenditures)

The operating expenditures for the systems operating at 95% capacity are evaluated in Table 6. These are composed of two parts: fixed charges and variable charges. Especially, investments in the mining of coal and its transportation, chemicals transport and CO_2 capture are also included in the estimation of variable costs. This was done in order to examine the influence of these variables on the economic benefits of the whole system.

The coal exploitation cost is 28.55 US\$ t^{-1}. Coal transportation cost is calculated according to the rail freight tariff rules in China by the following formula [35]: coal transportation cost (US\$ t^{-1}) = (1.5 + 0.013 × km) × coal (t), and a haul distance of 100 km from coal mine to processing plant. Methanol transportation cost is 24.48 US\$ t^{-1} and the CO_2 transportation and storage cost (US\$ t^{-1}) can be expressed as: US\$ $t^{-1} = 9.35 + 0.35 \times km^{0.483}$ [5]. The captured CO_2 is piped to Qinshui basin in Shanxi (a distance of about 300 km) for ECBM (Enhanced Coal Bed Methane) recovery. Cost of electric power transmission is 0.01 US\$ kWh^{-1}, a figure obtained from the National Development and Reform Commission [36].

The number of staff is supposed to be 250 in the case of IGCC, 300 for IGCC–CCS and IGCC–CRS, and 400 for the PL–CCS, D-PL and D-PL-CR on the basis of reference [37]. The staff salary is assumed to be an average of 7.14 US\$ h^{-1} with a standard work week of 40 h. Compared with PL–CCS or IGCC–CCS/CRS, the OPEX of D-PL-CR increase only by US\$ 6 million based on the D-PL. A list in order of expense can be given as: 1) PL–CCS; 2) D-PL-CR; 3) IGCC–CCS/CRS. Annual average fixed capital investment, raw material expenditure and operation and maintenance charges constitute 65% of the total investment expenditure. It is of great importance to develop technology with independent intellectual property in order to reduce fixed charges and look for alternative energies to reduce material costs, thereby improving the overall economic performance of all the systems.

3.4.3. Exergy cost

The composition and distribution of exergy cost during the life cycle production process for the systems under consideration are shown in Fig. 6. The unit exergy cost of raw coal increases from 2.19 to 3.30 US\$ GJ^{-1} after exploitation and transportation. In IGCC–CCS, the water–gas shift unit and CO_2 capture process during the clean-up phase lead to an increase in cost of about 1.59 US\$ GJ^{-1} for fuel gas sent to the gas turbine, an increase not incurred by IGCC/IGCC–CRS. However, in IGCC–CRS, fuel gas is burned in pure oxygen instead of air in the gas turbine, which increases ASU energy consumption. The added exergy cost of ASU can be taken as the increase of power generation cost, so the increment of power generation process is higher than other systems. D-PL-CR has a particularly low energy cost. Use of recycled CO_2 as the gasification agent in the gasifier can increase effective gas ($CO + H_2$) yield, rendering the raw gas exergy cost of D-PL-CR between 0.6 and 0.9 US\$ GJ^{-1} lower than that of other systems operating without CO_2 recycling. For D-PL-CR, the incremental exergy cost in the chemical process is embodied in the CH_4/CO_2 reforming unit, but this system avoids energy consumption in both the shift and decarburization processes. Moreover, CO_2 recycling requires minimal energy consumption, increasing effective gas while reducing overall technology cost. The final generating cost of D-PL-CR is more than 10 US\$ GJ^{-1} lower than that of the IGCC/IGCC–CCS/IGCC–CRS systems.

3.4.4. Cost of electricity (COE) analysis

COE can be calculated by the formula in the literature [16]. COE comparison of the systems is shown in Fig. 7. The COE of IGCC (0.08 US\$ kWh^{-1}) is 40% higher than the average feed-in tariff

Table 5
CAPEX of different systems.

					Evaluation	IGCC	IGCC–CCS	IGCC–CRS	PL–CCS	D-PL	D-PL-CR
						(US$ million)					
CAPEX	Depreciable capital	Fixed capital	Bare module costs	Equipment (*E*)	/	284.82	395.32	356.60	403.92	340.11	350.95
				Installation	4.1% *E*	11.68	16.21	14.62	16.56	13.94	14.39
				Indirect construction	8.7% *E*	24.78	34.39	31.02	35.14	29.59	30.53
				Contractor design	13.5% *E*	37.31	51.79	46.71	52.91	44.55	45.97
				Total (*M*)		358.59	497.71	448.95	508.53	428.19	441.84
			Cost of site preparation		2.5% *M*	9.03	12.44	11.23	12.72	10.71	11.05
			Cost of service facilities		2.5% *M*	9.03	12.44	11.23	12.72	10.71	11.05
			Total (*F*)		/	376.65	522.59	471.41	533.97	449.61	463.94
		Cost of contingencies			8% *F*	30.35	41.81	37.72	42.72	35.97	37.12
		Total (*D*)				407	564.4	509.13	576.69	485.58	501.06
	Cost of land				2% *D*	8.20	11.29	10.18	11.53	9.71	10.03
	Cost of plant start-up				5% *D*	20.49	28.22	25.46	28.84	24.28	25.05
	Working capital			Inventory	15 days of raw materials and chemical production	3.17	1.75	1.60	28.38	18.29	18.23
				Accounts receivable	30 days	13.17	13.17	13.17	41.37	33.89	33.89
Total CAPEX (US$ million)						452.03	618.83	559.54	686.81	571.75	588.26
Unit CAPEX (US$ kW^{-1})						1506.74	2062.79	1865.08	2289.36	1905.56	1960.89

(0.06 US$ kWh^{-1}, year of 2010 in China), and when the CCS subsystem is added, the COE increases by a further 40%–60%. Comparatively, the COE of PL–CCS is only about 70% of that of IGCC–CCS and IGCC–CRS. It can be concluded that chemical and power co-generation efficiently reduces COE, offsetting extra expenditure required by the CCS processes. D-PL and D-PL-CR show better performance, especially D-PL-CR, with a COE of 0.04 US$ kWh^{-1}. Combined with the previously energy use and CO_2 emission analysis, the D-PL-CR not only maintains high energy utilization efficiency, but also reduces CO_2 emission and COE. Overall, it is of greater economic and environmental benefit to undergo CO_2 conversion and utilization within the system as much as possible before CO_2 capture, transportation and storage.

3.4.5. *Influence of carbon tax on COE*

In order to investigate the effects of the carbon tax on the COE of a system, the contribution of CO_2 emissions reduction to COE can be defined as follows:

$$\mathrm{COE_{CCT}} = \mathrm{COE} - \frac{\mathrm{CO_{2,R}} \times \mathrm{CO_{2,Tax}}}{\mathrm{CF} \times 7200\ \mathrm{h} \times P} \tag{1}$$

where the $\mathrm{COE_{CCT}}$ represents the COE of systems with CO_2 capture or use considering benefits from CO_2 tax. If the systems can realize CO_2 emission reduction, the corresponding subsidies of CO_2 tax can be seen as a compensation for COE. $CO_{2,R}$ represents CO_2 emission reduction (t y^{-1}) of the systems, $CO_{2,Tax}$ represents CO_2 tax price (US$ t^{-1}). The second item in the eq. (1) means the reduction of COE caused by CO_2 emission reduction. CF is the plant capacity factor, P is the power output of the plant in MW.

Fig. 8 shows effects of the carbon tax price on COE of systems. When the carbon tax price reaches a certain point, the COE of systems with CCS may be even less than that of systems without CCS. For instance, when carbon tax is increased to over 20 US$ t^{-1}-CO_2, the COE of PL–CCS is lower than even that of D-PL and D-PL-CR. In a similar manner, an increases to 33 US$ t^{-1}-CO_2, renders the COE of IGCC–CRS equal to that of IGCC. As carbon tax continues to increase, systems with powerful CO_2 emission reduction ability become more economically competitive. A carbon tax is no doubt a powerful impetus to the development and application of low-carbon techniques. In China, application of carbon tax is still in planning stages, with implementation expected to begin before the end of the 2011–2015 five-year plan [38]. Compared with average tax levels in other developed counties (about 20 US$ t^{-1}-CO_2) [39], however, the initial carbon tax threshold is relatively low (1.5–3 US$ t^{-1}-CO_2) [38]. In this instance, under a weak carbon mitigation policy, D-PL-CR displays favorable economic performance.

3.5. *Sensitivity analysis*

Fig. 9a shows the variation of the unit CAPEX and carbon tax price with time. At an average annual growth rate of 15%, the carbon tax will reach about 10 US$ t^{-1}-CO_2 from an initial tax rate of 1.59 US$ t^{-1}-CO_2 [39] by 2025. On the basis of the current construction investment for IGCC/polygeneration system, and a supposed reduction rate of 2.5% per year, the present rate of investment could be reduced by as much as 18.4% by 2020. Fig. 9b presents the change of COE over time. By 2020, the COE of IGCC may be reduced to 0.07 US$ kWh^{-1}, but the COE of IGCC–CCS/CRS would remain over 0.08 US$ kWh^{-1}. In other words, when compared with conventional coal-fired power station, IGCC or IGCC–CCS/CRS shows no economic advantage. However, according to this developmental model, both PL–CCS and D-PL/D-PL-CR have the potential to reach a low COE.

The IRR (internal rate of return) is commonly used as an economic criterion to evaluate the feasibility of a project, and the higher IRR is, the more feasible it is to undertake a project. Fig. 9c shows that the IRR of IGCC will remain at about 6.5% until 2020, while IGCC–CCS/CRS display even lower IRRs. In contrast, PL–CCS and D-PL/D-PL-CR show good economic performance, and the IRR of PL–CCS is projected to outstrip those of D-PL/D-PL-CR after 2018. However, compared with PL–CCS, D-PL/D-PL-CR is more stable and less likely to be impacted by changes in carbon tax price. With a shortage of energy, coal prices will increase sharply, making this aspect a great challenge to the development of the IGCC/PL–CCS/CRS systems. Stabilizing the price of coal, exploring new alternative energies and enhancing the energy efficiency of systems are key factors in the sustainable development of CCS and related techniques.

Table 7 shows the comprehensive performance comparison of the six cases. With equivalent net power outputs of 300 MW, D-PL-CR shows the highest thermal efficiency at 53.03%, and other areas of performance, such as IRR and CO_2 emission are 17.86% and 0.62 kg kWh^{-1}, respectively. D-PL-CR displays the best comprehensive performance. Systems incorporating CO_2 recycling (IGCC–CRS and D-PL-CR) can effectively reduce the amount of steam required by the gasification process. In the case of IGCC–CRS and D-PL-CR, the ratio of steam/water to coal was reduced by 0.21 and 0.10 kg kg^{-1} respectively. Thus, valuable steam can be saved,

Table 6
OPEX of different systems.

			Evaluation		IGCC	IGCC–CCS	IGCC–CRS	PL–CCS	D-PL	D-PL-CR
							(US$ million)			
OPEX	Fixed charges	Operations	Direct wages and benefits ($W1$)	7.14 US$ h^{-1} (40 h $week^{-1}$)	3.77	4.44	3.42	5.99	5.99	5.99
			Direct salaries and benefits	13% $W1$	0.49	0.58	0.45	0.78	0.78	0.78
			Operating supplies and services	4% $W1$	0.15	0.17	0.17	0.24	0.25	0.25
			Total		4.41	5.19	4.04	7.01	7.02	7.02
		Maintenance	Wages and benefits ($W2$)	2.5% D	10.25	14.11	12.73	11.53	13.60	14.03
			Salaries and benefits	17% $W2$	1.74	2.40	2.16	1.96	2.72	2.80
			Materials and services	75% $W2$	7.68	10.59	8.91	8.66	10.20	10.52
			Maintenance overhead	3.5% $W2$	0.36	0.50	0.45	0.41	0.52	0.53
			Total		20.03	27.60	24.25	22.56	27.04	27.88
		Operating overhead	General plant overhead	5.2% ($W1 + W2$)	0.84	1.12	0.99	1.08	1.22	1.25
			Mechanical department services	2% ($W1 + W2$)	0.33	0.43	0.30	10.53	0.46	0.47
			Employee relations department	4.5% ($W1 + W2$)	0.73	0.97	0.83	0.91	1.04	1.07
			Business services	5.5% ($W1 + W2$)	0.89	1.19	1.05	1.12	1.27	1.30
			Total		2.79	3.71	3.17	13.64	3.99	4.09
		Tax & insurance		2% D	8.20	11.29	7.64	11.53	9.71	10.03
		Total (OP1) (US$ M y^{-1})			35.43	47.79	39.10	54.74	47.76	49.02
	Variable charges	Raw materials	Coal and COG		39.6	48.6	42.48	109.08	92.81	88.23
		Utilities	Process water and cooling water		0.59	1.59	0.57	4.54	1.81	1.88
		General expenses	Selling/transfer:	2% Sales	2.63	2.63	2.64	8.27	6.77	6.66
			Direct research:	1% Sales	1.32	1.32	1.32	4.13	3.38	3.33
			Allocated research:	0.5% Sales	0.66	0.66	0.66	2.07	1.69	1.67
			Administrative expenses	0.5% Sales	0.66	0.66	0.66	2.07	1.69	1.67
			Management incentives:	0.5% Sales	0.66	0.66	0.66	2.07	1.69	1.67
			Total		46.12	56.12	48.99	132.23	109.84	105.11
		System external expenses [5]	Coal exploitation & transportation	(30.53 + 0.013*km)* Coal (t)	21.00	25.77	22.53	57.85	14.60	12.98
			Chemical production transportation	24.48 US$ t^{-1}				6.77	4.97	4.86
			CO_2 Transportation and Storage	$9.35 + 0.35^{*}km^{0.483}$		30.76	31.91	45.90		
			Electric power transmission	0.01 US$ kWh^{-1}	21.94	21.94	21.94	21.94	21.94	21.94
			Total		42.94	78.47	76.38	132.46	41.51	39.78
		Total (OP2) (US$ M y^{-1})			89.06	134.59	125.37	264.69	151.35	144.89
Total OPEX (US$ M y^{-1})					124.50	182.39	164.48	319.43	199.10	193.70

resulting in a reduction of phenol water produced in the gasification process, especially in fixed bed gasifier (Lurgi, BGL etc.) [40] as well as a reduction in the load of wastewater to be treated. According to the research results, for D-PL-CR, the system can conserve coal at a rate of 5.0×10^4 t y^{-1} and COG at a rate of 3.0×10^7 m^3 y^{-1}, and reduce steam by 1.0×10^5 t y^{-1} and CO_2 by 1.3×10^5 t y^{-1}. These projections are much more favorable than those calculated for systems not incorporating CO_2 recycling.

3.6. *Extension for "dual-gas" polygeneration system*

According to the previous analysis, the dual-gas of CGG and COG polygeneration system is a good option for dealing with deficiencies such as low efficiency, heavy pollution and high investment cost typically associated with solely using coal or COG. Also, the "dual-gas" technology adapted for coal/biomass/heavy oil/waste-based gasified gas is not limited in scope to merely CGG or COG, but includes other resources (with equivalent components) such as NG (natural gas) and UNG (unconventional natural gas) (coal bed methane, shale gas, etc.). The generalized concept of DGP ("dual-gas" polygeneration) based on single-feed system not only produces multiple by-products but also integrates different types of primary fuel as feedstock. For DGP, according to energy level and chemical characteristics, select processes of energy conversion can be coupled together. As shown in Fig. 10, DGP has high fuel flexibility, allows for various combinations of electricity, alternative

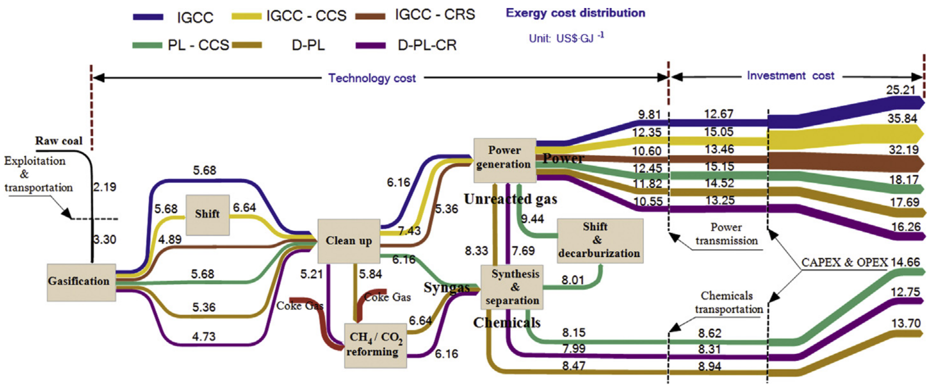

Fig. 6. The composition and distribution of six systems exergy cost in the life cycle of production process.

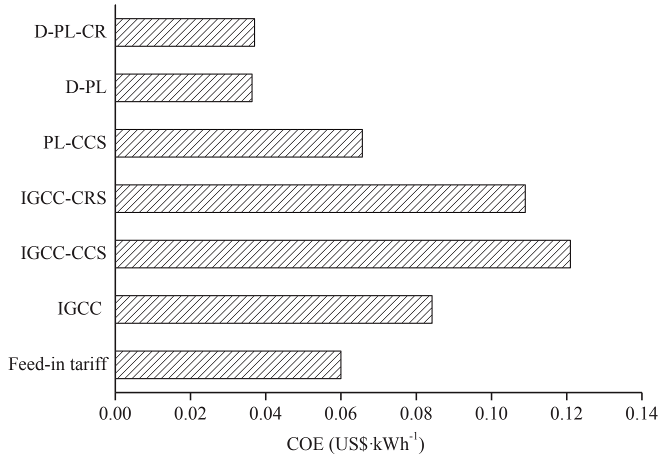

Fig. 7. COE comparison between the systems and feed-in tariff.

liquid fuels, hydrogen, chemicals and/or heat, and realizes efficient separation, recovery, and reuse of waste and other functions in energy conversion. More importantly, the advantage is that the water–gas shift reaction ($CO + H_2O = CO_2 + H_2$) is not necessary, and, more importantly, CH_4 and CO_2 can be converted and utilized, reducing fuel input and GHG emission as well as increasing the utilization efficiency of carbon resources. The dual-gas of CGG and COG polygeneration system with CO_2 recycling (D-PL-CR) evaluated in this paper is a suggested standard for the promotion and application of DGP.

4. Conclusions

Based on commercially ready technology with CO_2 recycling, a novel type of polygeneration system with CO_2 recycling is proposed. 3E analysis of the system showed promising results from many of the component schemes, from CO_2 recycling to the gasifier and reforming unit, reducing the amount of steam required by gasification and realizing the conversion and utilization of CH_4 and CO_2, rendering the conventional water gas shift process unnecessary. This not only reduces required fuel input, wastewater treatment load and resulting greenhouse gas emissions as a result of excluding the CCS process, but also increases the utilization efficiency of carbon resources and energy. More importantly, the "dual-gas" technology can be easily adapted to utilize other gases, such as NG or UNG, possessing components similar or equivalent to COG. Hence, for areas both rich in coal and source gases (NG, UNG, COG etc.), but with limited water supply, "dual-gas" and CO_2 recycling technology would be a clean, economic and efficient way utilize those energy sources. Research results showed that in the D-PL-CR system, 60 mol% of CO_2 from the chemical separation unit is recycled into the gasifier and the remaining 40 mol% is consumed by the reforming reactor, an optimal CO_2 recycling scheme. Under these conditions, at a power output of 300 MW, the system can potentially save 5×10^4 t y^{-1} of coal and 3×10^7 m^3 y^{-1} of COG, and reduce steam by 1.0×10^5 t y^{-1} and CO_2 emissions by 1.3×10^5 t y^{-1} in comparison to systems without employing CO_2 recycling.

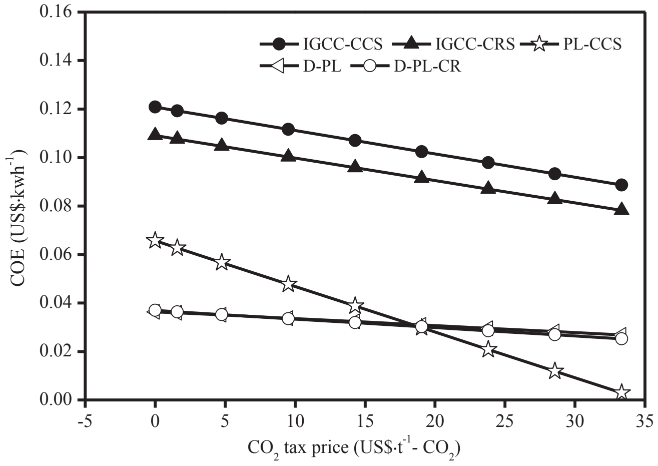

Fig. 8. Effects of the carbon tax price on COE of different systems.

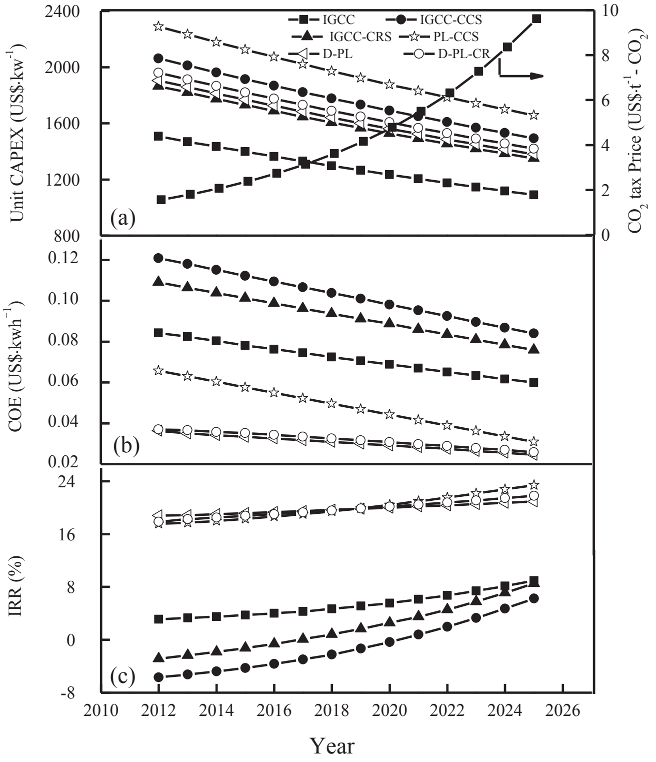

Fig. 9. The variation of unit CAPEX, carbon tax price, COE and IRR with time.

Table 7
The comprehensive performance in life cycle comparison among the six systems.

Items	IGCC	IGCC–CCS	IGCC–CRS	PL–CCS	D-PL	D-PL-CR
Coal input (t d^{-1})	2200	2700	2360	6060	1530	1360
Coke-oven gas input ($\times 10^6$ m^3 d^{-1})					4.35	4.25
Steam or water/coal input (m^3 kg^{-1})	0.64	0.64	0.43	0.64	0.62	0.52
O_2/coal input (kg kg^{-1})	0.92	0.92	0.88	0.92	0.71	0.69
MEOH output (t d^{-1})				2323	1695	1653
Gross power output (MW)	349	386	458	594	433	440
Net power output (MW)	300	300	300	300	300	300
COE (US$ kWh^{-1})	0.084	0.121	0.109	0.066	0.036	0.037
IRR (%)	3.12	−5.67	−2.84	17.54	18.8	17.86
Thermal efficiency (%)	38.39	29.95	33.94	40.39	50.86	53.03
CO_2 emission (kg kWh^{-1})	0.89	0.13	0.06	0.59	0.68	0.62
CO_2 capture (kg kWh^{-1})		0.96	0.93	1.44		
CO_2 capture rate (%)		90	97	74		

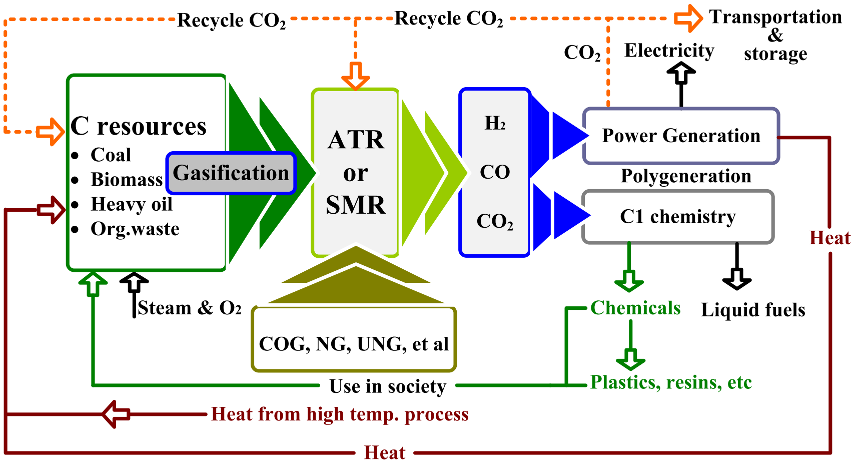

Fig. 10. Schematic diagram of generalized DGP system.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2014.01.053.

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